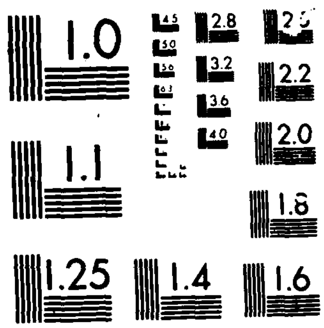
AD-A166 626 SENSITIVITY OF REFRACTIVE INDEX PROFILE MODELS TO RELATIVE HUMIDITY SENSOR ERRORS(U) NAVAL RESEARCH LAB WASHINGTON DC S G GATHMAN 27 MAR 86 NRL-MR-5750 1/1

UNCLASSIFIED F/G 4/1 NL



MICROCOP CHART

2

NRL Memorandum Report 5758

Sensitivity of Refractive Index Profile Models to Relative Humidity Sensor Errors

S. G. GATHMAN

Atmospheric Physics Branch
Space Science Division

AD-A166 626

March 27, 1986

NAVAL RESEARCH LABORATORY
Washington, D.C.

153

AD-A166636

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5758	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory — 6b. OFFICE SYMBOL (If applicable) Code 4110	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION NAVAIR — 8b. OFFICE SYMBOL (If applicable) AIR 333	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20361	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
63207N	W0514	A3303301	DN480-588

11. TITLE (Include Security Classification)
Sensitivity of Refractive Index Profile Models to Relative Humidity Sensor Errors

12. PERSONAL AUTHOR(S)
Gathman, S. G.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Interim	FROM ______ TO ______	1986 March 27	40

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The problem of errors in the measurement of relative humidity from radiosondes and their possible effects on the detection of radar ducts in the boundary layer are discussed. Some numerical studies of the detection algorithm are presented. A statistical study of horizontal variations in relative humidity in the marine boundary is presented as a limitation on the accuracy requirement for data feeding into programs such as IREPS. A discussion of sensor development and a summary of sensor intercomparisons is included for completeness.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Stuart Gathman	22b. TELEPHONE (Include Area Code) (202) 767-2022 — 22c. OFFICE SYMBOL Code 4110

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

CONTENTS

1. EXECUTIVE SUMMARY 1

2. BACKGROUND 3

3. NUMERICAL EXPERIMENTS 5

   3.1 Sampling Period Errors 6
   3.2 Systematic or Bias Errors 7
   3.3 Random Errors 7
   3.4 Lag Errors 7
   3.5 Hysteresis Errors 8

4. IREPS SENSITIVITY 8

5. PERFORMANCE OF HUMIDITY SENSORS 11

   5.1 History of the Carbon Humidity Element 12
   5.2 Laboratory Tests of the Sondes 13
   5.3 Review of Multi-Radiosonde Flights 14

6. CONCLUSIONS 18

7. RECOMMENDATIONS 19

8. ACKNOWLEDGMENTS 20

9. REFERENCES 35

SENSITIVITY OF REFRACTIVE INDEX PROFILE MODELS
TO RELATIVE HUMIDITY SENSOR ERRORS

1. EXECUTIVE SUMMARY

This report attempts to answer the question of how sensitive the products of a potential major user of the data from the MINI-REFRACTION SONDE, (MRS) system, are to errors in the currently available commercial relative humidity sensors proposed for use by the Navy. In particular the report looks at the IREPS, (Integrated Refractive Effects Prediction System) (version 2.2) computer program which predicts the refractive bending of electromagnetic radiation due to the nonuniform index of refraction occurring in the earth's atmosphere. This model gives estimates of the effective slant range a particular system will have if given appropriate inputs.

Under certain types of atmospheric refractive index profiles, extraordinarily long ranges may be possible because of a ducting process in the atmosphere which is, in some aspects, similar to the wave guide phenomena in microwave propagation. The atmospheric layers where this propagation occurs are known as ducts. Several geometric features of these ducts are important in the long range propagation such as the location of the top of the duct and its thickness, and its relative strength.

The refractive index of any part of the atmosphere can be calculated from the measurable meteorological parameters of pressure, temperature, and water vapor concentration. Thus profiles of the atmospheric refractivity can be obtained by sounding the atmosphere with meteorological balloons. The question to be asked is--How much error can be allowed in the measurement of water vapor before serious errors in the IREPS predictions of range will occur?

A series of numerical simulations were done on the computer in which a typical assumed profile of meteorological parameters was used as a "true" profile. This profile contained two ducts, the geometric properties of which we know exactly. Various mathematical descriptions of measurement error were then introduced into the values of water vapor and their effect on the geometric properties were noted.

Secondly, a special data set is used to give some statistics on the horizontal inhomogeneity of the marine atmosphere. The rationale for these measurements is the notion that the maximum accuracy required for the humidity sensors is equivalent to the magnitude of the errors in the horizontal homogeneity assumption.

Manuscript approved January 28, 1986.

Finally, the paper reviews studies in which the two competing sensor technologies (the VIZ carbon element and the Vaisala Humicap sensor) were compared with each other. Dual radiosonde flight comparison of the devices is the technique used in making this analysis. The main problem with the dual flight comparisons is that the true profile values are not known. All that can be gathered from these data is how the devices differ from each other and not how they differ from the actual values existing at that spot at that time in the atmosphere. The authors use a number of assumptions in making their conclusions about the devices.

The consensus of these papers is that, in general, the spread in the values which the individual sensors measured at the same time and place in the atmosphere can be quite large. If this large spread of data were used in a sensitive IREPS model, a very large spread in predicted ranges could occur. On the other hand, the large spread of data would have little or no effect on the predicted range of IREPS if it were relatively insensitive to these errors.

This author is not convinced that the spread of measured data is the result of one type of sensor being right and the other wrong as some of the authors representing one or the other of the two sensor groups like to contend. Rather this uncertainty is the result of the same physical processes affecting the two types of sensors in different ways. As the exact cause of this variance is not apparently known, it must be assumed that an uncertainty of the parameter value of this amount might exist. A real possibility is that existing commercial sensors may not always be accurate enough to keep the IREPS prediction errors to within reasonable values. This result is complicated by the problem of horizontal variations in the index of refraction, which if present, could cause prediction errors even with a perfect sensor. It is nevertheless advisable to keep the measurement as good as possible to maximize the number of valid cases where the model and data accuracy are compatible.

The accuracy of either MRS humidity sensor could be improved if an adequate correction algorithm existed to compensate for the errors and to thus correct the measurements. This of course requires a consistency in manufacture of the sensors. This situation would also require good laboratory measurements whereby the sensors can be compared with a known standard under many physical conditions likely to be encountered in the atmosphere.

A second recommendation would be to modify IREPS to the extent that it would provide a statistical element in its products whereby insensitive solid predictions based even on shaky input data would be identified by high probabilities of range prediction accuracy and cases where there is a sensitivity to input data would be indicated by a lower probability in its range prediction.

A third approach for the measurement of profiles of temperature and water vapor would be to use the LAP (Lidar Atmospheric Profiler) shipboard lidar for this measurement. Although the effect of clouds in screening the upper atmospheric levels, eye safety, and the overall

accuracy and reliability of such a system operating at sea are yet to be demonstrated, such a system offers many potential advantages especially in its ability to average out horizontal variations by repeated sampling. Also, the vertical range of the LAP needs considerable improvement before being capable of replacing radiosondes.

2. BACKGROUND

The accuracy of the measurement instrumentation used to obtain input data for the operation of models such as IREPS (Hatten et al., 1983) is very important. A model similar to IREPS will be included in TESS (Tactical Environmental Support System) and will become an important user of the SMOOS (Shipboard Meteorological and Oceanographic Observing System) data. The specific problem addressed in this report is the effect of measurement error in MRS relative humidity data (which are stored by SMOOS) and used on the calculations which produce the products of IREPS. There are reported differences in the responses of the relative humidity sensors used in the instrument packages from different manufacturers. This difference is primarily the result of two physically different techniques used in the humidity sensing process. This reported difference exhibits itself when one balloon carries aloft two or more different radiosonde packages. Although this difference is thought to be most significant as the radiosonde passes through a cloud in its ascent into a dry subsaturated region, differences in the instrument measurements may also be observed under less dramatic atmospheric changes. Errors in these measurements, if used with IREPS, may cause significant errors in the position of radar ducts and the ranges predicted by the model.

The electromagnetic predictions of the IREPS program are dependent on the vertical profile of the modified refractivity of the atmosphere supplied to it. This profile is assumed to exist through out the immediate area of operation and is used for predicting the bending of radar frequency waves which is the basis for the products of the model. The shape of the so-called "M" profile (M standing for the modified refractivity) determines the existence of trapping layers in the atmosphere. When these layers exist, the so-called radar ducts may allow the detection of targets at much greater than normal (or over-the-horizon) distances. This phenomenon is the result of the radar waves propagating within these ducts very much as they would in a wave guide. Both elevated ducts and surface based ducts exist and are important in the operation of radars and other electro-magnetic systems at sea.

The index of refraction of the atmosphere, i, does not change a great deal within the atmosphere and therefore the changes which are important to the refraction of radar waves are reflected in the least significant digits of the refractive index value. In order to amplify these variable parts, a more sensitive description of the index of refraction is a function N called the refractivity of the atmosphere or simply, N-units. It is defined as:

$$N = (i - 1) \cdot 10^6 \tag{1}$$

The value of N can be calculated in terms of the important meteorological quantities of the atmosphere as such:

$$N = \frac{77.6\ P}{T} + \frac{3.73 \cdot 10^5\ e}{T^2} \tag{2}$$

where P is the pressure measured in millibars. T the temperature in degrees Kelvin, and "e" the water vapor pressure of the atmosphere in millibars. These parameters can be determined by a radiosonde instrument. The modified refractivity, M, is used for convenience and is essentially the same as N except that the trapping gradient of N with respect to height has been eliminated. This parameter is very useful in determining the presence of ducting. M is given by:

$$M = N + 0.157h \tag{3}$$

where h is the altitude measured in meters.

The general flow of information in the IREPS model is shown in figure 1. This figure shows the sensors used to obtain the data inputs for the model and on which the model bases its estimates for its products. There are several levels of accuracy represented by the data inputs and of course the predicted output estimates are no better than the quantity of the data used in making these estimates. The IREPS program is designed to work under all types of conditions even when there are no input data available. In this latter situation, a climatology input is used and the estimate is then based on past measurements which are close to that particular time of year and place. The estimate using this type of data input is itself only applicable in the broad, climatological sense but if no other real time measurements are available, then this is valuable.

The most direct data input is, of course, a straightforward measure of the refractivity profile by an aircraft microwave refractometer. These data aren't always available, however, and flight path irregularities and horizontal variability in refractive index may cause additional errors even when it is available. Thus, the radiosonde input for meteorological data converted to index of refraction is an important source of data for input into IREPS. This report will look at specifically how the accuracy of the relative humidity sensor of the radiosonde will affect the accuracy of the products of IREPS.

3. NUMERICAL EXPERIMENTS

A series of computer simulations were done in an effort to determine the characteristics of the geometric perturbations which are introduced into the modified refractivity profile when various types of errors in the measurement of relative humidity the radiosonde instrument are assumed. An artificial, perfectly defined set of pressure, temperature and relative humidity functions were produced over the first kilometer of the marine boundary layer. These time functions were constructed in such a way that both a surface duct and an elevated duct were present in the refractive profile. The basic duct characteristics of this artificial profile were not unlike the profiles containing both surface and elevated ducts from the 120 oceanic profiles studied by Werst (1980). The pressure, temperature, and relative humidity data were made into completely smooth analytical functions. A finite number of points were used to initially determine the general shape of the three profiles. An analytic expression for these variables was made by using cubic splines fitted to the original points. For the purposes of this analysis, the values determined from the cubic splines will be considered as the "true" profiles of pressure, temperature, and relative humidity as a function of time. The question of accuracy can then be addressed by introducing realistic errors in the observation of relative humidity and to see how these measurement errors will affect the geometry of the ducts. The true values of pressure, relative humidity and temperatures are shown as profiles of T and RH plotted with respect to altitude in figure 2. A constant ascent rate will be assumed for these analyses.

The modified refractivity profile M(z) for this case is plotted in figure 3. It is calculated from the values of water vapor pressure, atmospheric pressure, and temperature using equations 2 and 3. By definition the relative humidity (measured by the radiosonde) is 100 times the mixing ratio of the air sample divided by the saturation mixing ratio at that temperature. Since we are given a measurement of the air temperature, the saturation mixing ratio at that temperature can be calculated by the Goff-Gatch equation, List (1968) and the relationship between the mixing ratio, the water vapor pressure and the atmospheric pressure. This value together with a measurement of the relative humidity allows a determination of the mixing ratio of that parcel of air to be made. The water vapor pressure of the parcel of air in question is then related to the mixing ratio, r and the ambient pressure, P by:

$$e = \frac{r \cdot P}{0.62197 + r} \qquad (4)$$

The altitude of the top of a duct is detected by observing at what point the sign of the gradient of M(z) changes from negative to positive. If a vertical line is drawn down from this point where it either hits the surface or again intersects the M(z) curve, the bottom of the duct is located. If it hits the surface without intersecting M(z), the duct is called a surface duct; otherwise it is known as an

elevated duct. The artificial profiles used in this numerical analysis were designed to have both a surface duct and an elevated duct in the same profile to see if there were differences in the behavior of the detection algorithm for the two different kinds of ducts when error was introduced into the relative humidity input data.

With this mechanism it is now possible to simulate various kinds of errors in the relative humidity measurement and to make some kind of statement as to how these errors will affect the determination of the geometry of the apparent refractive index profile as compared with the "true" refractive index profile which was used prior to the introduction of errors in measurement.

3.1 Sampling Period Errors

The first potential source of error that will be introduced into the observations has to do with the period of time that elapses between successive observations. The knowledge that is given to us through the sensors is finite and fine structure of the atmosphere could be lost in between observation points. It is obvious that if the data sampling rate is very slow, the duct structure may be missed entirely. In making this simulation, we will assume that the sampling period is "dt" and that because of the randomness of the precise time of launch with respect to the onboard clock, that the first point of measurement will be a random fraction (between 0 and 1) of the sampling period dt. Since the data for relative humidity, temperature, and pressure are assumed exact, for a given dt, the only difference between the various computer runs is in the time of launch and the altitudes at which the measurements are made. The resultant error in duct geometry, as determined by the measurements, can be plotted in terms of the sampling period, dt. The rate of ascension for these experiments was assumed to be constant at a value of about 3.67 meters per second. For each sampling period, 20 different profiles were obtained each differing from each other by the altitude of the first observation.

The result of the simulation is plotted in figure 4. In this figure are three dashed horizontal lines which represent the true duct surfaces which were obtained from the smooth function of the data shown in figure 3. For each of the various assumed sampling periods, the ducts are represented by vertical lines and the rectangles at the extremities of each line represent the standard deviation of the data from the mean of the 20 profiles at that dt value. It is seen that as the sampling period reaches over 30 seconds, the coarseness of the sampling period with respect to the time spent in the structure starts to cause problems in the ability of the algorithm to accurately locate the tops and bottoms of the ducts. The standard deviation increases for the increased sampling period and the error between the mean and the true value increases as the sampling period increases. The data of figure 4 show the effect of sampling rate on duct geometry determination for a particular ascent rate and a particular atmospheric structure. The sondes presently planned for MRS utilization provide a sampling time of 4 seconds or less; this rate should handle the data easily and produce a minimum of error from this source.

3.2 Systematic or Bias Errors

The second type of error which was simulated is that of fixed systematic errors. The plot shown in figure 5 shows the estimated duct altitudes from radiosondes with fixed error of from -10 percent relative humidity to + 10 percent relative humidity. The data shows that these type of errors have little effect on the location of the ducts or their sizes. Although this type of error may cause other types of problems, they do not apparently cause large effects on the duct detection algorithms used by IREPS. The sampling period for this set of runs was 12 seconds and the randomness of starting position is still included. The temperature and pressure data was untouched and only the relative humidity was given a fixed offset from its correct reading. This is essentially the type of error which would be caused by a bad calibration error.

3.3 Random Errors

The third type error which was considered was that of random error in the relative humidity measurement. By this type of error we mean that at any level the true value of relative humidity might be somewhere between a value and either a plus or minus term which was a random fraction between 0 and 1 of the maximum random error given in the figure's abscissa. This type of error could of course cause a lot of trouble in real soundings because erroneous gradients might be inferred (even using perfect sensors) from horizontal variability in the atmosphere. This noncompliance of the real atmosphere with our assumptions of horizontal homogeneity can cause a large error in the determination of the duct geometry. This type of error is similar in form to noise. The response of our system to this type of error is shown in figure 6. Here we see that small errors are tolerated by the system, but if the noise level reaches levels exceeding 2 percent relative humidity, the output data become unreliable. A fix, however, for this problem would be to oversample the atmosphere in an attempt to average out these types of errors or to provide data smoothing, such as least squares regression.

3.4 Lag Errors

A fourth type of error which was investigated with these numerical experiments is that of the response lag of the relative humidity sensor to real rapid changes in ambient relative humidity. In a private conversation, Helvey (1985) pointed out that in reality the response of these devices is complex and in the case of the VIZ carbon element humidity sensor is the superposition of three different lag processes. For simplicity, the numerical simulation here is only one lag but it could be thought of as being the superposition of several shorter lags. The plot shown in figure 7 shows how the ducts appear to be at higher and higher altitudes as the lags increase. There doesn't seem to be a systematic growth in the standard deviation as the lag increases although there are several isolated cases of large standard deviations, the exact cause of the large standard deviations is not known and is probably just the result of random processes.

3.5 Hysteresis Errors

A fifth type of error known as a hysteresis error can be simulated with this numerical approach. There is indication from radiosonde users that the relative humidity sensors as well as the temperature sensors will experience hysteresis-like problems when they encounter high relative humidity layers and/or clouds topped by dry layers. We will try to simulate this hysteresis by causing the calibration characteristics of the relative humidity sensor to change after experiencing "wet" values of relative humidity greater than 90 percent and to "dry out" after the relative humidity reaches lower than 20%. This simulation, shown in figure 8, assumes that there is no error in the relative humidity until the value is greater than 90% RH. Once this level has been achieved, then the measurement error is described by a function which is linear with the ambient RH between 100% RH and 50% RH. This error function levels off to a constant offset at relative humidities between 50% and 20%. If the relative humidity drops below 20% then the original dry curve is in effect. The wet error curve approaches zero at 100% RH and the level of error at 50% is used to differentiate one curve from the other in the plots. A result of a set of experiments is shown in figure 9 which shows the distortion in the duct geometry that can be experienced if the humidity sensor has a hysteresis-like characteristic. The x-axis shows the error magnitude parameter represented by the value of the error at 50% RH. The figure shows the true values of the ducts top and bottom as horizontal dashed lines. It is interesting to note that the algorithm locating the top of the duct is not noticeably affected by the size of the hysteresis error where as the algorithm locating the bottom of the duct shows a small linear relationship with respect to the magnitude of the hysteresis error. The behavior is expected because the duct tops are determined by slope changes in the modified refractivity where as the duct bottom is directly related to relative humidity values.

Although these simplistic simulations of sensor errors do not describe in detail how a real sensor would respond to the idealistic profile of this study, it can be used as an indicator of trends for generic types of error and show how these different types of errors will effect the duct geometry algorithms used by programs like IREPS. It seems from these studies that the only type of error which would not make a difference in the detection and location of the duct geometry is that of a constant offset in the calibration. The other types of errors, if kept to within reasonable bounds, should not cause a great deal of damage to the determination of the duct geometry calculation.

4. IREPS SENSITIVITY

It has been shown how errors in relative humidity might change the geometry of the refractive ducts in the marine environment. What has not been shown is how these errors might translate into the prediction of important products of the IREPS program such as range of detection etc. One difficulty in this investigation is the large number of variables that the program must take into account. As with any computer program it is virtually impossible to try every permitted combination of

the model parameters. Therefore, in order to determine the sensitivity of IREPS to errors in relative humidity, there is an almost infinite set of parameters which must be used in runs. If the problem is narrowed down to a particular profile, then a sensitivity to inputs might be determined. However, even though one radar detector at a particular elevation and with a particular set of propagation characteristics may be very sensitive to the geometry of the refractive profile, other radar sets with different transmission characteristics or the same set at different elevation might be very insensitive to these profiles.

The best that can be done is to devise a set of statistical probabilities related to the occurrence for each type of E.M. equipment at each location as well as the probability of occurrence of all types of refractive profiles over the ocean. Our very sensitive case might not even exist in the real ocean or it might exist quite commonly. Only a complete statistical study can answer this question. Unfortunately under the scope of this project, we do not have an adequate probability climatology of refractive ducts [except for the limited set described by Werst (1980)], nor do we have the statistics on the equipment and location that might occur in real life.

An alternate approach is needed whereby the accuracy of the humidity sensors required for the successful operation with a computer program like IREPS can be determined. One assumption that is necessary in IREPS for its successful prediction is that the atmosphere is horizontally homogeneous. The program requires a single profile of atmospheric parameters and then assumes this represents the whole area about the place where the sounding is made. Since in real life there no doubt are small horizontal gradients or changes in the meteorological environment about the place where the profile is made, then it is apparent that as long as the errors in the relative humidity measurements are no larger than the magnitude of the differences between two different profiles in the same local area, then those instrument errors can not adversely effect the operation of IREPS any more than the required assumption of horizontal homogeneity within the area. This then can be used as a gauge for the accuracy requirements of the relative humidity measurements. If both humidity sensors can easily be better than the gauge, then either one can be used. Likewise, if both cannot ever reach this requirement, then it makes no difference which one is used. It is only important when during some significant part of the time one device is clearly better than the gauge and the other device is clearly worse than the gauge.

In order to attempt to answer this question, some actual measurements made in the marine atmosphere will be used. The data for this report does not purport to be a true statistical sample of world-wide horizontal gradients but it does give some guidelines for the accuracy needed by humidity sensors for marine use. The reasoning here assumes that a humidity sensor does not need to have error bars which are less than those introduced by the uncertainties in horizontal gradients. The extra accuracy, though useful for other purposes, is not needed for this particular purpose.

The measurements for this analysis were done at San Nicolas Island, California in October 1984 with a single highly accurate instrument package supported by a tethered balloon, Gerber(1985). Relative humidity was measured by the dry/wet bulb technique with very small and fast thermistors (matched to .005 deg C). Individual temperatures were determined to have an over all accuracy of .05 deg C and the wet bulb (as well as the dry bulb) were ventilated by natural means with the instrument always being aligned into the wind by the action of the balloon and it's tether line. When the measured wind speed at the instrument level was less than 3 miles per hour, the measurements were not used. The advantage of this technique is that a single instrument can be used for all of the tests and the changes in the profile over the period of an hour and be accurately compared.

The data used here represent two altitudes, the one at 200 feet being always within the marine boundary layer during these flights and the other at 2000 feet being almost always above the marine boundary layer during these flights. The values of measured relative humidities at each of these altitudes was recorded on the ascent and again on the descent of the tethered balloon. The time between the two observations was always between 20 minutes and 90 minutes. The difference in relative humidity from these flights as well as a scaled parameter (produced by dividing these differences by the wind speed and by the delay time) will be presented to investigate the net size of these differences.

The data is presented on log normal probability plots in figures 10 through 13. A straight line representing the least squares fit to the log normal probability data is also presented for each of the cases. These plots can be used to extract some interesting information about the statistics of these measured parameters as they exist in the marine environment. These plots show that there is more variation in the relative humidity profile within the marine boundary layer than above it (ie at 200 feet than at 2000 feet). This is an expected result because of the complex turbulent process taking place in this region as compared with the other layers. Figure 10 shows at 200 feet, the most likely difference in the relative humidity observations between the ascent and the descent is about 7%. In this case approximately 90 minutes elapsed between readings. For the probability band of between 20% and 80% a range in relative humidity differences of about 1% to 20% RH is expected. In the 2000 feet data, the same analysis shown in figure 11, predicts a most probable difference of 1.5% RH and a spread of from .8% RH to 3% RH for the probability band of 20% to 80%. Of course at this altitude the time between observations is shorter (on the order of 20 to 30 minutes depending on the maximum height that the tethered balloon accomplished that flight). Therefore it might be argued that the time between observations at 2000 feet being closer to the apex of the flight is smaller than that of the 200 feet measurement and that this is the cause of the discrepancy. Therefore the scaled data called here the horizontal gradient in relative humidity is plotted in figures 12 and 13. These data show that at 200 feet the 50% probability value of the horizontal relative humidity gradient was 0.4% per mile with a band spread of from .05 % per mile to 2% per mile for the 20% and 80%

probability levels respectively. At 2000 feet however the most probable horizontal relative humidity gradient was about 0.2% per mile with a band spread of from 0.1 to 0.4%/mile for the 20% and 80% probability levels. From these data then an estimate can be given for the degree of horizontal homogeneity for a circular area of radius 25 miles from the original observation site. From this extrapolation we can expect that 50% of the relative humidity values within the marine boundary layer will show relative humidity differences at 200 feet of :

$$25 \text{ miles} * 0.4 \text{ \%RH per mile} = 10 \text{ \%RH}. \qquad (5)$$

and that only 25 % of the profiles would be expected to have differences of less than 2% relative humidity. For larger areas, the degree of non-homogeneity can be expected to be even larger although it is not necessarily expected to be a linear function for large extrapolations.

From this data analysis it can be concluded that relative humidity accuracies of less than 2% RH are not needed by IREPS 75% of the time. The problem is that horizontal variability becomes important and if horizontal variations of this magnitude exist, then even a perfect sensor would not solve the problem, and errors in measurement would be masked by these horizontal variations if they are of the same magnitude.

5. PERFORMANCE OF HUMIDITY SENSORS

The question discussed in this section is whether or not the capabilities and accuracies of the presently available relative humidity sensors can even meet the requirements listed above. It is now time to look at the basic relative humidity sensors used in the Beukers and Vaisala radiosondes being considered for the Navy's MRS system, and to try to determine the capability and problems of these devices and their ability to provide the data needed by IREPS.

The data base available for this discussion is not adequate for the job. The data base is derived from two distinctly different sources. The first source is from multi-radiosonde flights in which radiosondes of various kinds are compared. The problem with this mode is that the true meteorological variables existing in the atmosphere at the time of the flight are unknown and the net result of the experiment is that the difference between various radiosondes are determined but the elusive absolute accuracy of an individual instrument can only be inferred by this type of experiment. Of course if one of the radiosondes in the multiparcel flight is known to be more accurate than the others, then the results of the flight approaches the desired end in which the unknown sensor is compared to a standard. The second source is from laboratory experiments in which the sensors were exposed to controlled conditions.

The Beukers radiosonde uses the VIZ carbon element as its relative humidity sensor. The Vaisala sonde uses their own manufactured sensor

called the "Humicap". The VIZ sensor is a carbon element type which has a long history of application in radiosonde service. The sensor has been steadily improved over the years and certain of its shortcomings have been overcome by correction tables and algorithms. The Vaisala device on the other hand, is a relative newcomer in the field. The "Humicap" is a thin film capacitive type humidity sensor, the physics of which is not well described in the open literature. The Vaisala Company claims an accuracy of +/- 2% RH and a response lag of 1 second at a ventilation flow of 6 meters per sec at 1000 mb and 20 degrees C.

5.1 History of the Carbon Humidity Element

Research on the carbon humidity element was started in 1942 when Dr. E. K. Carver of Eastman Kodak Research Laboratory suggested the concept to C. W. Brasefield of the US Army Signal Corps Research Laboratory (Stine, 1965). It wasn't until much later that, according to Mathews (1965), the carbon element emerged from its long laboratory phase in 1957. It was in this year that this device was flown in comparison with the then standard lithium chloride sensor. Although the first flights showed little difference between the two types of sensors, the carbon element showed superior speed of response at low temperatures and higher accuracy at the wetter relative humidities as more data were gathered. Finally in 1963 the carbon element became operational with the US Weather Bureau.

This method of electric hygrometry using carbon elements became the standard humidity sensor for radiosondes because of its accuracy at wide ranges of relative humidity. In 1965 it was still under development, however, in order to overcome certain difficulties in mass producing units with stable calibration properties (Showalter, 1965). Even with those problems, the carbon element sensor was the best device available at that time for radiosonde probes.

This type of sensor has lag errors which are a function of temperature as well as a function of relative humidity. Unfortunately these errors become intolerably large for upper air work at very low temperatures. Experiments have been conducted to try and restore data of a sounding by attempting to account for the time lag by various mathematical techniques. Marchgraber and Grote (1965) attempted to describe the dynamic behavior of the then standard carbon element (ML-476). They used sophisticated analog computer techniques in these studies but were frustrated by the variation in element behavior between samples. This type of technique, because it is not unlike differentiation with experimental data, tends to be on the unstable side. Theoretically such techniques could be used to correct for response time but in practice such techniques have difficulties.

Another type of error which has been encountered with carbon radiosondes is a hysteresis problem which is believed to be primarily a surface effect of the carbon film. When the ambient humidity is decreased, the number of water molecules per unit surface area decreases. The surface then tends to bond together and contract, consequently trapping water molecules that have been absorbed into the

body of the film. This type of error can of course be corrected by using mathematical correction models. The capability of modern computers could allow complex data correction routines which could adjust to the current history of the individual humidity element that is encountered during the profile. The chief problem with this technique is again that of stability of sensor behavior. This might be accounted for by better quality control in the manufacturing process or perhaps by a more elaborate calibration procedure for each individual sensor (rather than assigning a fixed lock-in resistive calibration number to a large lot of sensors).

A third source of error in early carbon humidity elements was called humping which is a tendency of the carbon films to demonstrate a negative resistance humidity slope at humidities in excess of 90%. This phenomenon is thought to be mainly a result of ionic "poisoning" of the material during manufacture. Modern devices have overcome the third source of error and have apparently made modest improvements in the other sources of error. However, the carbon element is not yet perfect.

5.2 Laboratory Tests of the Sondes

In the laboratory, the range of conditions must simulate the kinds of environments likely to be encountered in the real atmosphere. Here, unlike in atmospheric flights, the accuracy of the controlled conditions are known because laboratory quality instrumentation are used in these tests. This approach has been used by the National Weather Service who sponsored laboratory tests on an older model VIZ carbon element sensor (made prior to June 1980) and the Vaisala Humicap humidity sensor, in the environmental test chamber at the National Bureau of Standards laboratory.

While it is common knowledge that a distinct improvement in the VIZ sensor has been made in the manufacture of the carbon sensors after June 1980, the release of the results of these tests on the VIZ sensors made before this date should show at least the general behavior of the sensor types which are based on different physical principles. Unfortunately the results of VIZ tests cannot be released by the NWS to public at this time because of litigation problems. (The results can be obtained by various government agencies from the NWS with permission). Therefore in fairness we should not discuss the merits or failures of one of the devices on the basis of these tests without looking at both sets of test data. Hence the only direct absolute measurements of these different generic sensor types and their behavior with respect to known standard values cannot be considered in the evaluation of these devices. The only data that can be used to make an evaluation of the relative capabilities of both sensors come from multi-radiosonde comparisons. As valuable as these multi-radiosonde flights are in comparing one unknown instrument with another, the absolute accuracy of the devices cannot be determined in this manner.

It is my opinion that without direct measurements of absolute accuracies made with a standard device, the capability of the sensors in question (and therefore an impartial evaluation of one sensor over the other) should not be made.

5.3 Review of Multi-Radiosonde Flights

There are several reports appearing in the literature that describe the results of multi-radiosonde flights. These data can be used to give an estimation on the typical relative accuracy of the sensors, if not the absolute accuracy. There are many factors that must be considered in addition to the differences between the two types of humidity sensors. Some of these factors are:

- What is the reproducibility of a profile if two different radiosondes from the same manufacturer are used on a single multi-radiosonde flight?

- Can a proper calibration of the element be done prior to flight?

- Can correction algorithms can be used to correct for known flaws in the data?

Consider the dual VIZ flights described by Richner and Phillips (1981). They report that their humidity data showed significant discrepancies between different VIZ sensors on the same flight. They showed that the instrument accuracy depends on the calibration point of the relative humidity sensor i.e., if the calibration were done at 10 degrees C and at 30% RH then an uncertainity of only 3% RH resulted between identical sensors. On the other hand if the calibration were done at 10 degrees C and 90% RH, then the uncertainty was as much as 15% RH. VIZ claims that 33% RH is the value used to calibrate their sensors because at this relative humidity, the sensor is virtually insensitive to the actual ambient temperature.

They estimated that the time constant of the humidity sensor was on the order of 3 seconds at 1000 mb pressure and a ventilation velocity of 5 meters per second. But they show that the time constant is a function of the pressure, temperature and the ventilation velocity, as well as the direction of the water vapor transport. They also state that the VIZ sensor recorded lower humidities than other sondes (ie the Swiss Meteorological Institute sonde and the Vaisala RS-18 sonde) when in air which was near saturation. They show from their three ascents all with the same sensor, that the standard deviation of the data with respect to itself went from a low of 1.5% RH to a high of 2.8% RH. This is only the reproducibility of the VIZ sensor system with respect to itself and does not reflect errors with respect to what the true humidity was.

Annema et al., (1984) refer to a series of flights in which three commercial radiosondes were compared in the multi-sonde flight mode. Of interest to this report is the comparison of the RS80 sonde which uses the Vaisala Humicap sensor and the Beukers microsonde which uses the VIZ carbon resistance sensor. Of a total of 15 flights, only 4 were a

direct comparison between the Vaisala and the Beukers instruments. The authors give a particular example (figure 1d in their paper) in which the sounding was taken through an 8/8 stratus deck while the output of the sensors was plotted. These data (taken in the near freezing area of -5 to 0 degrees C) show that the Vaisala humidity sensor detected the dry region above the inversion more rapidly than the VIZ sensor although the indicated rate of decrease in the relative humidity at the inversion was higher for Beukers than for Vaisala. In all of the examples given in this paper, the Vaisala sonde seemed to detect the dry layer before or at the same time as the other systems indicating that from this very limited sample that the Vaisala was as fast or faster than the other humidity sensors in detecting the dry layer above the cloud deck. These authors, using simple tests in the laboratory, assigned an accuracy to the Vaisala system at 20 degrees C and 60% RH, to be about 5%. The VIZ sensor could not be tested because of pressure contact switch and antenna problems.

Nash (1984) compared the Vaisala sonde with other good standard European sondes (the FRG Graw M60, Kaymont Airsonde AS-TH, and the UK RS3). He found that with respect to the "standard", Graw M60, the RS80 tended to under estimate relative humidity at the wetter end of the scale near the ground but it did give readings closer to the "standard" then the UK RS3 sonde. These data were taken in regions of no hydrolapse in order to minimize the influence of time lags of the sensors. The Vaisala sensor flown with a protective rain cap in place was shown to have a significant mean under-estimate with respect to the Graw M60 of at least 5% RH in the moist layers near the ground and this under-estimate increases in magnitude with respect to the "standard" Graw M60 as the altitude increases.

Phillips and Richner (1981) show, in the comparison between the VIZ sensor and the Swiss (SMI system) that the VIZ sonde always registered humidities less than 100%RH. In this experiment which was done in 1976, the Vaisala Humicaps were not yet in use and the VIZ sensor was of the older type. However, these data did show that the carbon element had trouble with the measurement of relative humidity in the presence of fog and in the high or wet end of the humidity scale.

Helvey (1979, 1982, & 1983) discusses the problem produced by radiosonde errors on spurious refractive ducts. He showed that mishandling of the carbon element sensors on the ground prior to launch can cause serious error because of thermal lag in the hygristor. Examples are given of heating of the carbon element before release due to solar radiation and of insufficient ventilation or of taking the sensor from an air conditioned calibration shack into a tropical atmosphere which caused the temperature of the carbon element to be different from ambient and ultimately causing a bias in the climatological studies of surface based refractive ducts. Because of this seemingly small error in the standard radiosonde data, spurious surface-based ducts were found which did not really exist in the first instance, and false sub-refractive layers in the second case were reported. Such findings shows the importance of our quest for adequate radiosonde data for input to an IREPS type model.

Phillips and Richner (1983) report on the experiment called "SONDEX", which compared 10 commercial types of radiosondes. In this experiment two of the sonde types used the Vaisala Humicap sensor for relative humidity measurement and two other types used the VIZ carbon element relative humidity sensor. In all, 154 radiosondes were flown in both multiple and parallel flights in central Europe. The data reported from this test are from only the 15 so-called "standard or mandatory levels" and no particular emphasis was given as to the structure of the atmosphere (i.e. significant levels) during the tests nor were the existence or the non-existence of saturated levels pointed out in the published report. These flights were all done in a non-marine environment so that the results do not directly transfer to the Navy's problem.

The SONDEX results however, show some very disturbing facts on the state-of-the-art in relative humidity measurements from balloon-borne radiosondes. It must be kept in mind that their "standard" by which the individual sondes were compared was the mean from all of the profiles. These data showed surprisingly large differences between different radiosonde packages using the same relative humidity sensor. For instance the VIZ sensor (at night) on the Sprenger E076 sonde showed deviations from the mean of from -15% RH to 0% RH whereas the same sensor on the VIZ 1392 sonde showed deviations from the mean of from -7.5% to 0% RH. The Vaisala sondes showed even worse response during the same night flight with the Humicap on the RS21 sonde giving errors of from -25% RH to 0% RH and the RS80 sonde going from -15% to 13% RH. This very different behavior between the RS21 and the RS80 indicates that perhaps different correction algorithms are used in their respective processors. The nature of these algorithms remains unknown to the general user.

Antikainen and Hyvonen (1983) discuss the accuracy of the Humicap relative humidity sensor of their company's radiosonde, the Vaisala RS80. They carried out 32 full-length dual high altitude Vaisala/Vaisala soundings with reported mean absolute differences between sets of dual sondes ranging from 2% RH at the surface to 3% RH at 200 mb.

J. Sniscak (1985a) in an unpublished NADC summary, reviewed a number of data sets in which either the VIZ and/or the Vaisala sensors were involved. This summary included tests made by the NWS and the Vaisala company. In this outline of his review only the data involving the humidity sensors are included. Papers from his summary which appear in published form and which deal with the humidity sensors are dealt with separately in this paper. The net conclusions of his unpublished summary of the data are:

- In the NWS qualification trials, Vaisala did not recover as rapidly as did the VIZ sonde after passing through a saturated layer.

- These same NWS trials showed that in general, the Vaisala indicated higher RH than VIZ.

- The Vaisala company in commenting on the NWS trials stated that the apparent errors were caused by a faulty glass encapsulation procedure for the thermistors.

- Vaisala reports Vaisala/Vaisala dual flights with the RS80 radiosonde yielding a mean absolute difference between instruments of 0.9% RH.

- Vaisala also gave a plot of the time lag function of the humidity device which is a function of temperature and relative humidity which might be used to correct the indicated reading from the device.

A further significant comparison of the Vaisala MRS system and the PMTC VIZ/GMD system was done by NADC and PMTC on the California coast in July 1984 (Sniscak (1985b)). These tests, summarized by Sniscak showed how the Vaisala sensor and the VIZ sensor compared when measuring refractive ducts in the atmosphere. His first observation was that the Vaisala reports weaker M-unit deficits of a particular refractive duct than does the simultaneously flown VIZ system. Secondly, he says that the Vaisala reports the ducts as thinner than does the VIZ system. This observation is similar to the behavior shown in the results for the computer runs at the beginning of this paper. The hysteresis error shown in figure 8 could explain the results of the PMTC test if a hysteresis error in the negative direction in the VIZ system were existing and the Vaisala system were operating properly. On the other hand, the Vaisala may have had a lag or hysteresis error in the positive direction. Again, we don't know which device is correct or if either of them are. We can only compare one against the other. The necessity of absolute testing of these devices under all conditions is again shown to be important.

From this same set of data, Sniscak looked at the particularly troubling region where differences between the VIZ and the Vaisala humidity sensors show up the most often. This is the dry region above clouds into which the probes enter after having been in the high humidity parts of the clouds. Sniscak calculated the speed of response expressed in % RH change per second for 16 cases where the probes were lifted out of the cloud into the dry air above the cloud. These data show that for a particular situation, the VIZ responded significantly faster than the Vaisala in 14 of 16 cases, with the remaining 2 cases being equivalent. It should be noted that in 10 of these 16 cases, the ambient temperature was much higher than freezing. In figure 14 the ratio of these speeds is shown plotted as a function of temperature of the probe. There is a slight indication of a temperature dependence of the ratio but certainly this is not very significant. The mean ratio of the speeds of the two sensors is about 0.7. The maximum speeds found from all these cases was 4.6 %RH per sec for the VIZ sonde and 2.34% RH per second for the Vaisala sonde.

If we want to see how discrepancies in these data affect the IREPS predictions, we can make some calculations with these figures if certain approximations are made. Assume first a perfectly sharp cut off between the 100% RH in the cloud and a very dry upper layer of 10% RH. Using the recovery speeds given above the VIZ probe would take roughly 13 seconds to go to "1/e" of the total excursion between 100% RH and 10% RH whereas the Vaisala probe would take about 25 seconds for similar excursions. These values (a rough indication of the lag of the systems) are certainly slower than the values reported by the companies but of course this is a worse case situation. If these lag times are used in looking at the errors in duct geometry described in figure 7, we see that even this worse case situation would not cause too much of a problem in the location of the duct surfaces.

Pratt (1985) discusses the errors which exist in the NWS archives of upper air data. He claims that although the magnitude of the temperature errors are generally 1 degree C of less, that the relative humidity measured with VIZ carbon hygristors can be low by 20 to 30 percent relative humidity under unfavorable conditions. He shows that although NWS requires that the hygristor error to be within 5% RH of the true value for all relative humidities above 30% RH and 7% for low temperature relative humidity measurements, the problems of hysteresis and ageing of the sensors can give rise to errors which exceed the specifications.

6. CONCLUSIONS

How can we choose between these two different sensor devices? It is obvious that if the requirements of IREPS are very stringent and the accuracies of the sensors are not very good, then it really doesn't matter which device is used. Neither of them will satisfy the requirements although we might wish to minimize the probability of wrong predictions by maximizing the accuracy of the input data. On the other hand, if the accuracies of either of the devices is better than that needed by IREPS, then in this case it really doesn't make any difference which device is chosen. It is certainly a matter of importance in choosing between the devices when one is clearly better than needed by IREPS and the other is clearly worse than needed by IREPS.

Several additional factors must be looked at when considering the selection of a radiosonde humidity sensor. It is probable in light of field tests of these devices that the errors that are exhibited by the devices are not independent of the varying conditions that are encountered by the device as was assumed by Antikainen & Hyvonen (1983). They appear indeed to be the result of different sets of circumstances happening to the probe during the course of its profile flight and therefore give rise to hysteresis-like errors. Situations such as liquid water clouds around the freezing point might cause unusual behavior for the sensors. In fact most experimenters I interviewed talk about the problems associated with the hysteresis effects on the sensor after it has been exposed to high relative humidities or clouds.

When trying to decide between one or the other when there is no clear cut issue on which to make the decision, the carbon element has the advantage of a long history on which to base correction formulas. There have been several attempts in the past to model the less than ideal behavior in the carbon relative humidity sensing element and to therefore improve its overall accuracy. The Humicap sensor being the newer system and having many of its aspects not yet accepted by the community suffers because (to my knowledge) correction formulas for this device are not available yet in the open literature. It is obvious from the review of literature cited above, that either device can give relative humidity data which are better than the 5% value used as a specification for the hygristor performance most of the time under ideal conditions. However, there are times when differences between sensors much greater than this are encountered in the test flights. Clouding the whole picture is the question of horizontal variation which if the analysis shown above can be believed, have variations of this magnitude and could cause IREPS to give erroneous products even if perfect sensors were employed. Unfortunately, there are no other alternatives on the shelves waiting to replace these sensors. The Navy still needs the use of programs such as IREPS regardless of the fact that some of the predictions might be wrong because of errors in the measurement of relative humidity profiles from the sounding equipment in use. It therefore is important to minimize the amount of wrong predictions by minimizing the errors in the profile data. There are reports in the literature of isolated cases where both types of sensors cannot make the 5% specification. The statistics of which one fails the most often would be nice to have but at present, there are not enough tests of the sensors against good standards to make this judgement.

7. RECOMMENDATIONS

A complete set of laboratory tests needs to be done on the new VIZ humidity sensors to determine the exact behavior of these sensors to the conditions likely to be encountered in regions important to refractive ducting in the marine environment. Of special interest is the problem of hysteresis behavior in the wet part of the scale. The Humicap sensors have been tested to some degree by the Bureau of Standards already. These data were not discussed earlier because of the fairness concept and the litigation problem implied above. If new VIZ data were available then these data could be used for comparison purposes. These laboratory data can be used to develop correction algorithms which is the best approach for coming up with a solution to the accuracy question.

The carbon elements have a long open history which can be used as background data for the work on this algorithm. It is possible however that the manufacturing process is near its maximum performance (due to its 45 years of development time already) and further improvements for this specific use (detection of refractive ducts) will not be forthcoming.

The Humicap sensor, on the other hand, is a new and promising technology. It suffers from the problem of trade secrecy in which only Vaisala seems to know exactly what its capabilities are and what algorithms to use with the system. It is interesting, but not surprising, that when the probes are used by the company the performance is spectacular, but when the instrument is used by others many problems appear. This may be because the company knows when to fly the devices so that poor operating conditions are not encountered or it may be because certain precautions are done by the company personnel to insure good results. These luxuries may not be possible to accomplish with non-scientifically trained help as may be the case for Navy applications.

A second recommendation would be to modify IREPS to the extent that it would provide a statistical element in its products whereby insensitive solid predictions based even on shaky input data would be identified by high probabilities of range prediction accuracy whereas cases such as the super sensitive case discussed above would indicate a low probability in its range prediction.

A third approach for the measurement of profiles of temperature and water vapor would be to use the LAP shipboard lidar for this measurement. Although the effect of clouds in screening the upper atmospheric levels, eye safety, and the overall accuracy and reliability of such a system operating at sea are yet to be demonstrated, such a system offers many potential advantages especially in its ability to average out horizontal variations by rapidly making many soundings.

8. ACKNOWLEDGMENTS

I wish to thank various members of the Navy community for their help in my putting together this paper. In particular I would like to acknowledge Roger Helvey of PMTC, John Sniscak of NADC, and H. Hitney and R. A. Paulus of NOSC for reading the manuscript, making constructive comments and suggestions many of which have been included in the revised manuscript. I also want to thank these people for the many practical discussions on the problems of making radiosonde measurements and on the operation of the IREPS in using these measurements. The author is indebted to the Navy's S.M.O.O.S. program and for the sponsorship of Mr. T. Czuba of NAVAIR for carrying out this work.

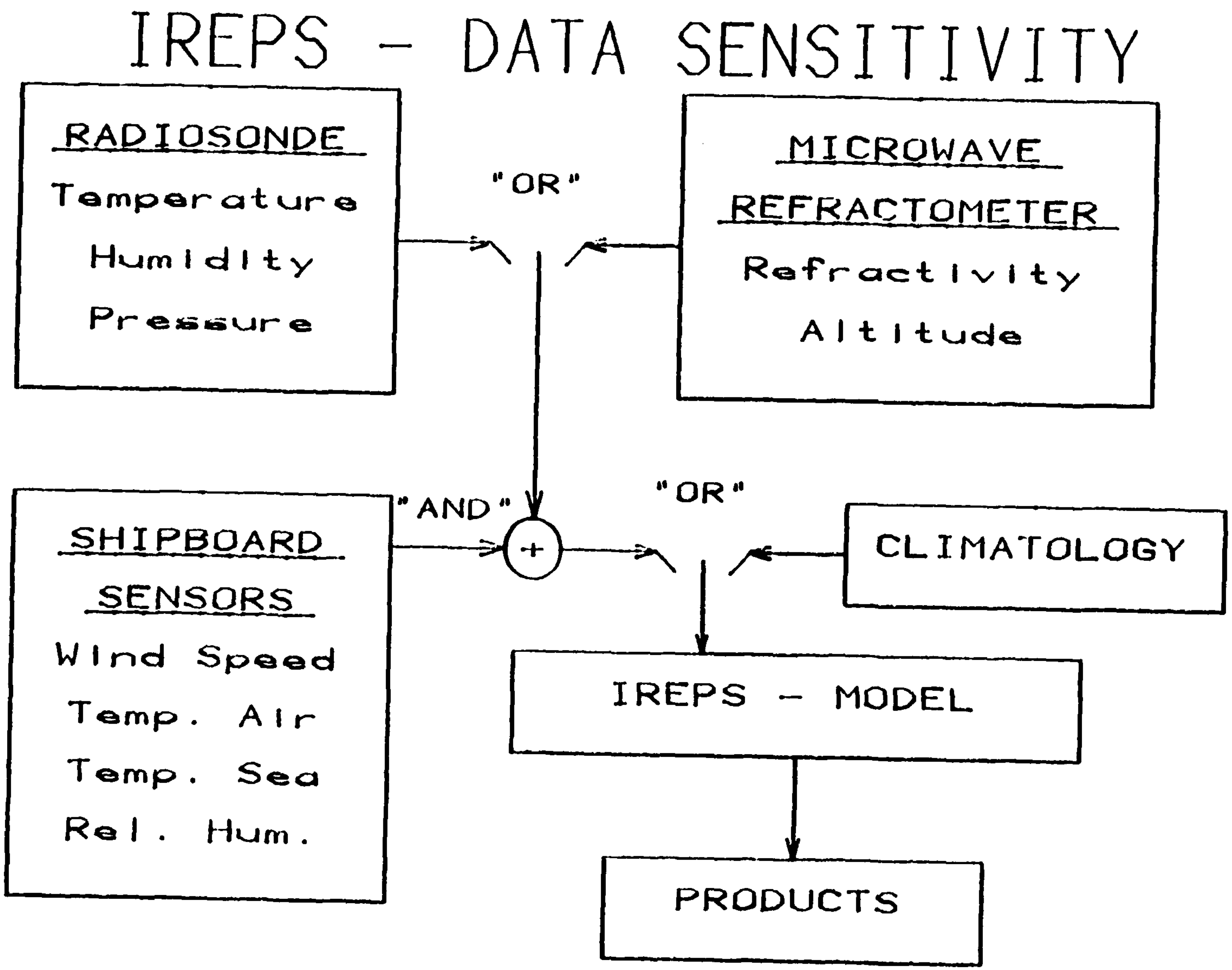


Fig 1 Data flow chart of IREPS model.

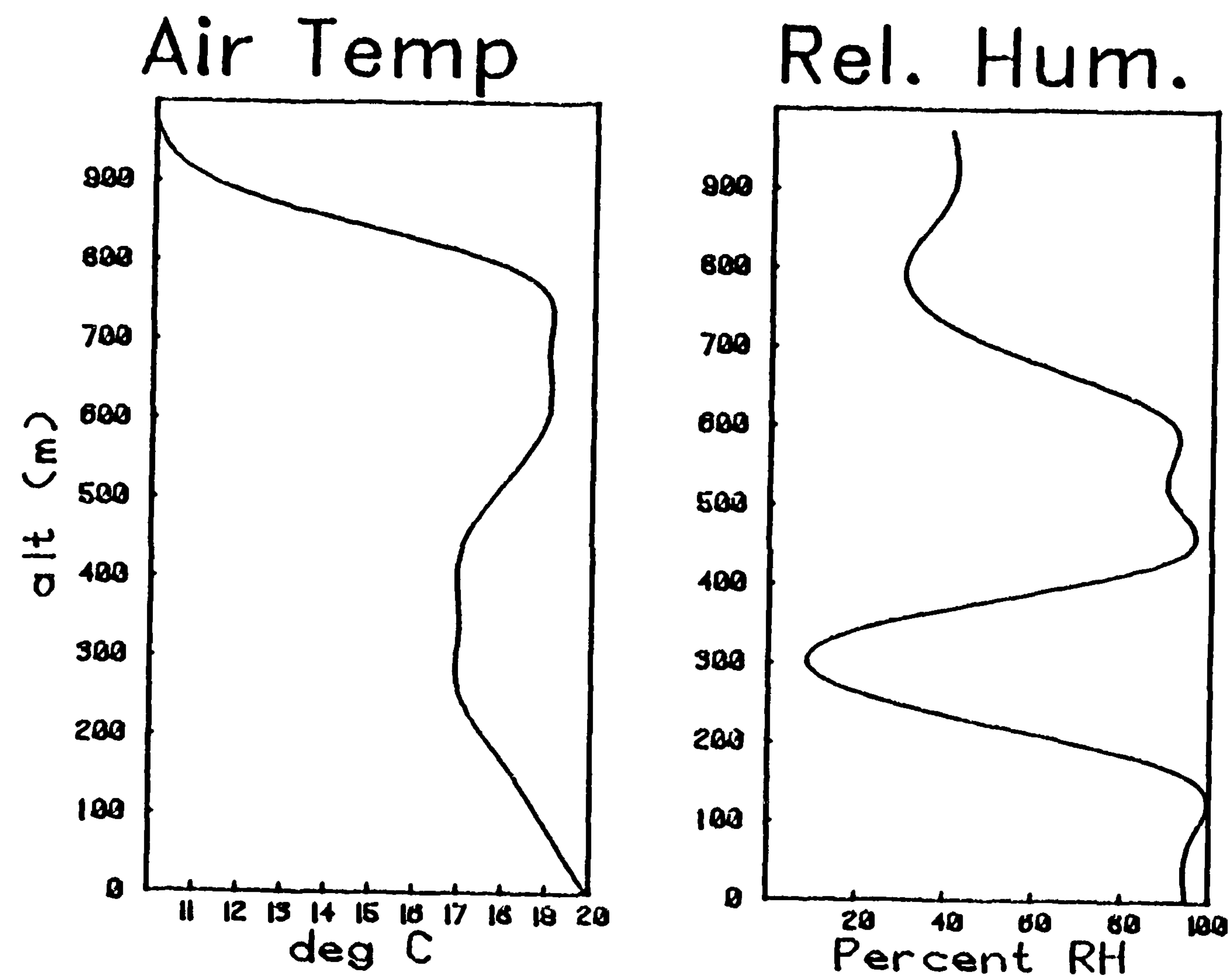


Fig 2 Profiles of air temperature and relative humidity used as the true values for the numerical sensitivity tests.

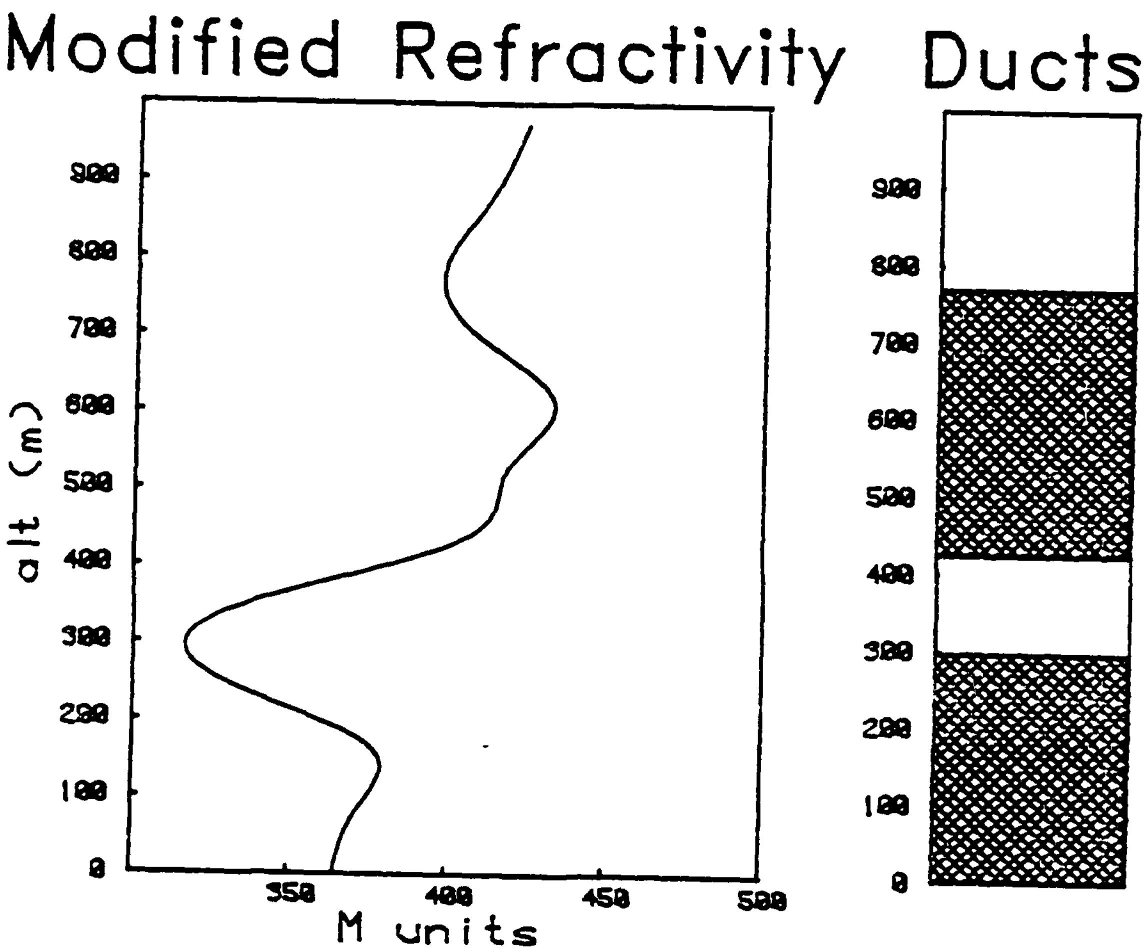


Fig 3 Profiles of the modified refractivity and the ducts associated with this profile as used in the numerical sensitivity tests.

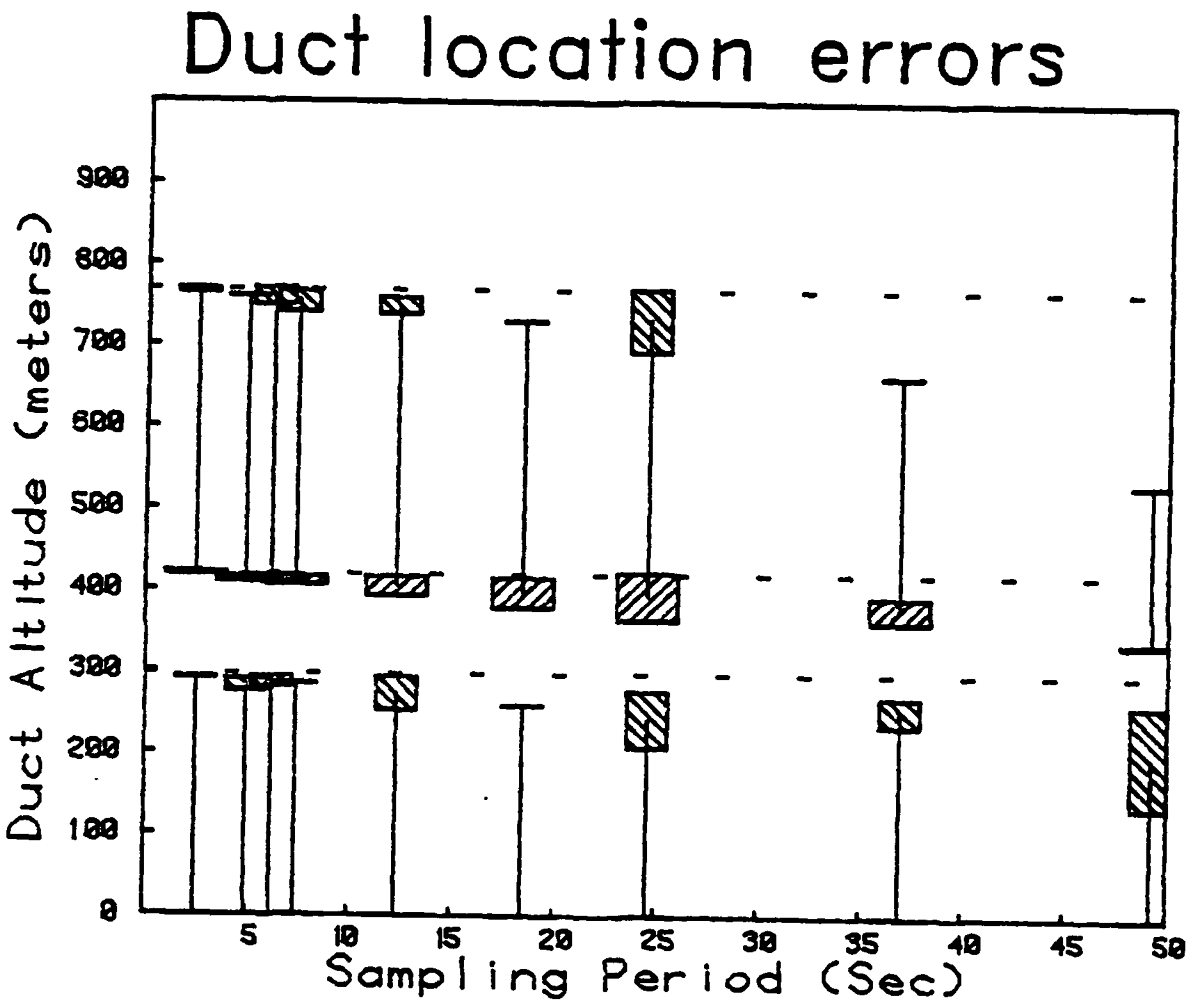


Fig 4 A plot of the duct location errors produced by sampling speed problems. The three horizontal lines are the true values, the vertical lines are the mean duct locations, and the boxes are the standard deviations in the location of the duct edges as computed from 20 random tests.

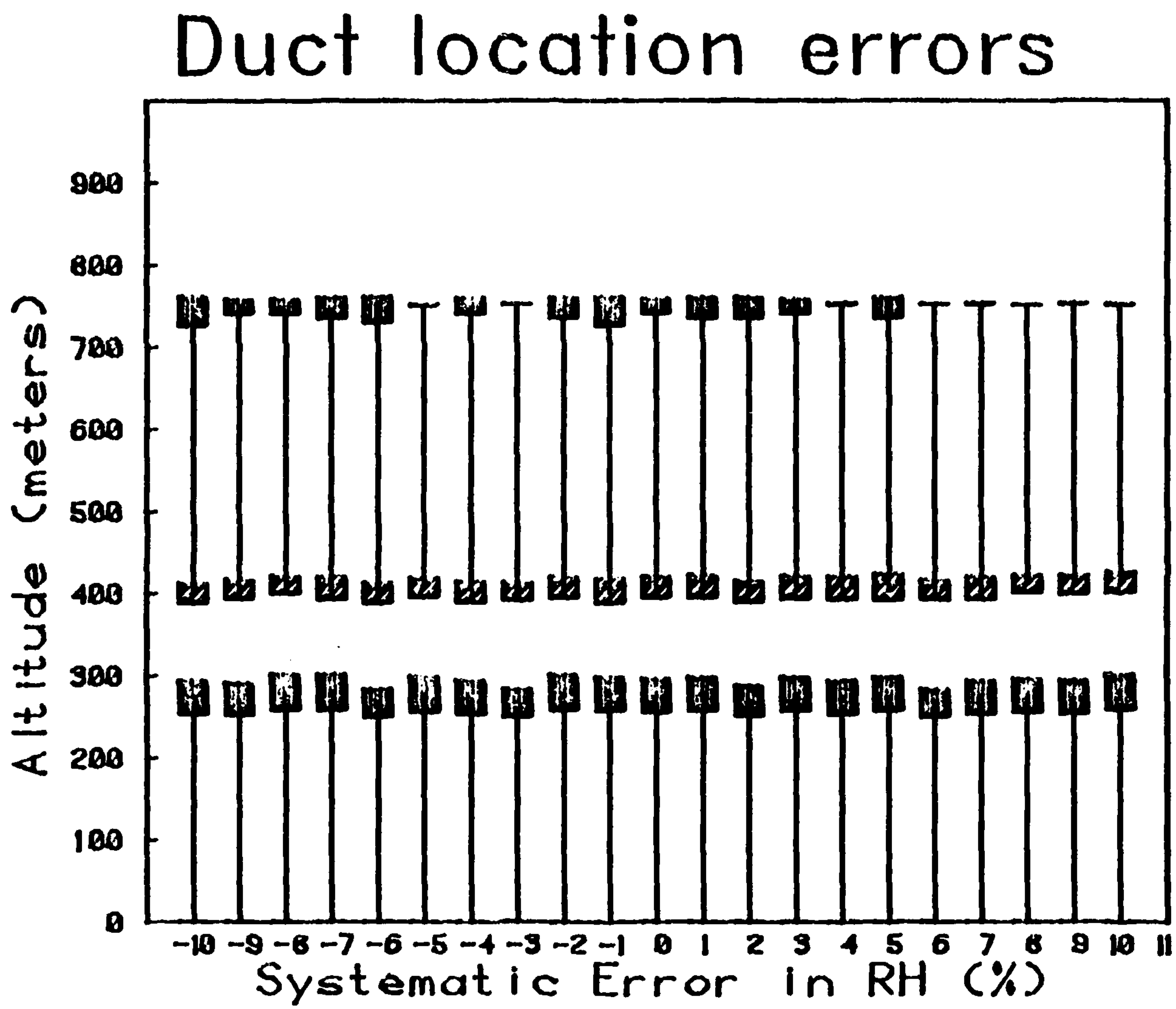


Fig 5 A plot of the duct location errors produced by a fixed systematic error or bias error in the value of indicated relative humidity.

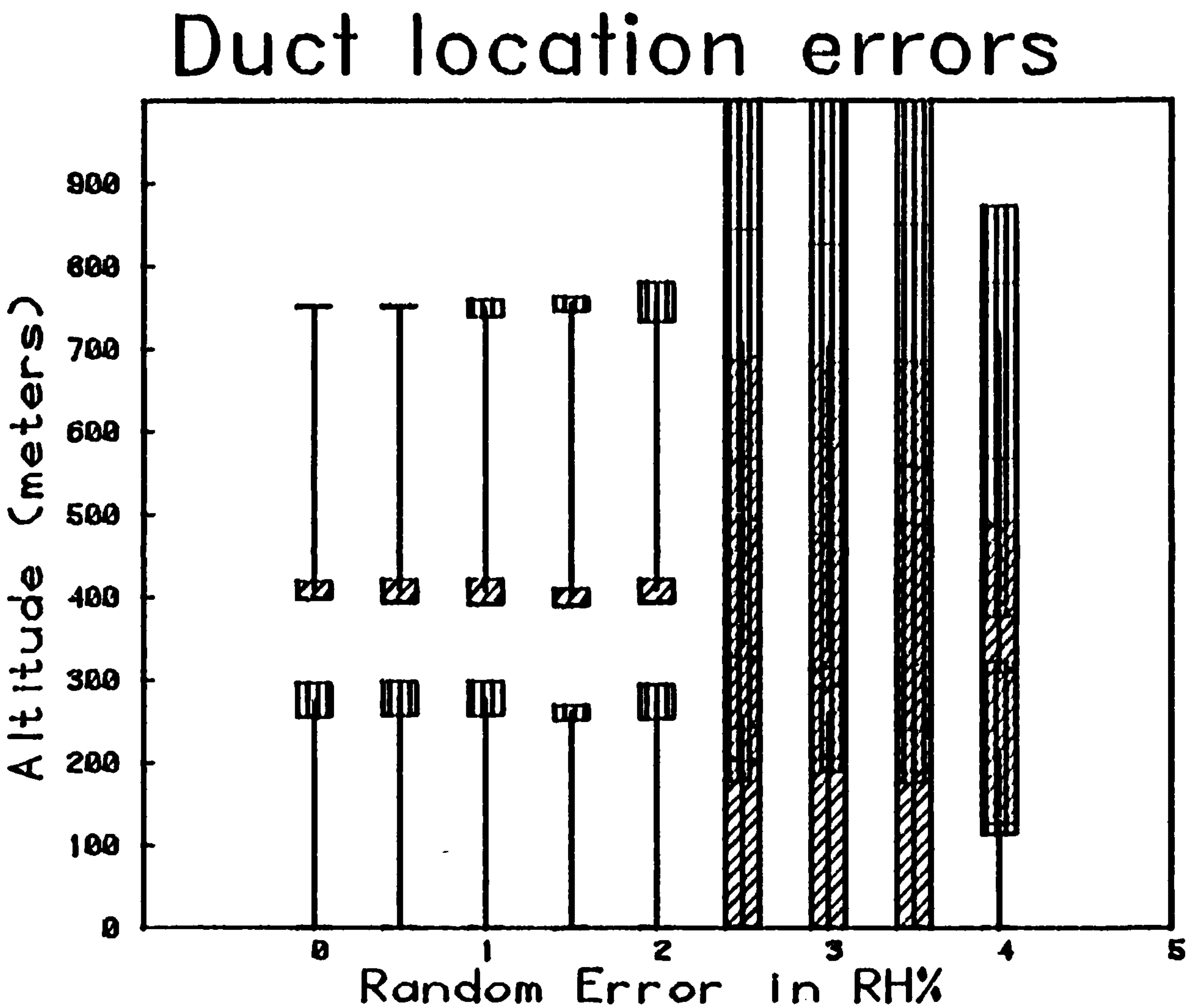


Fig 6 A plot of the duct location errors produced by random errors in relative humidity measurements.

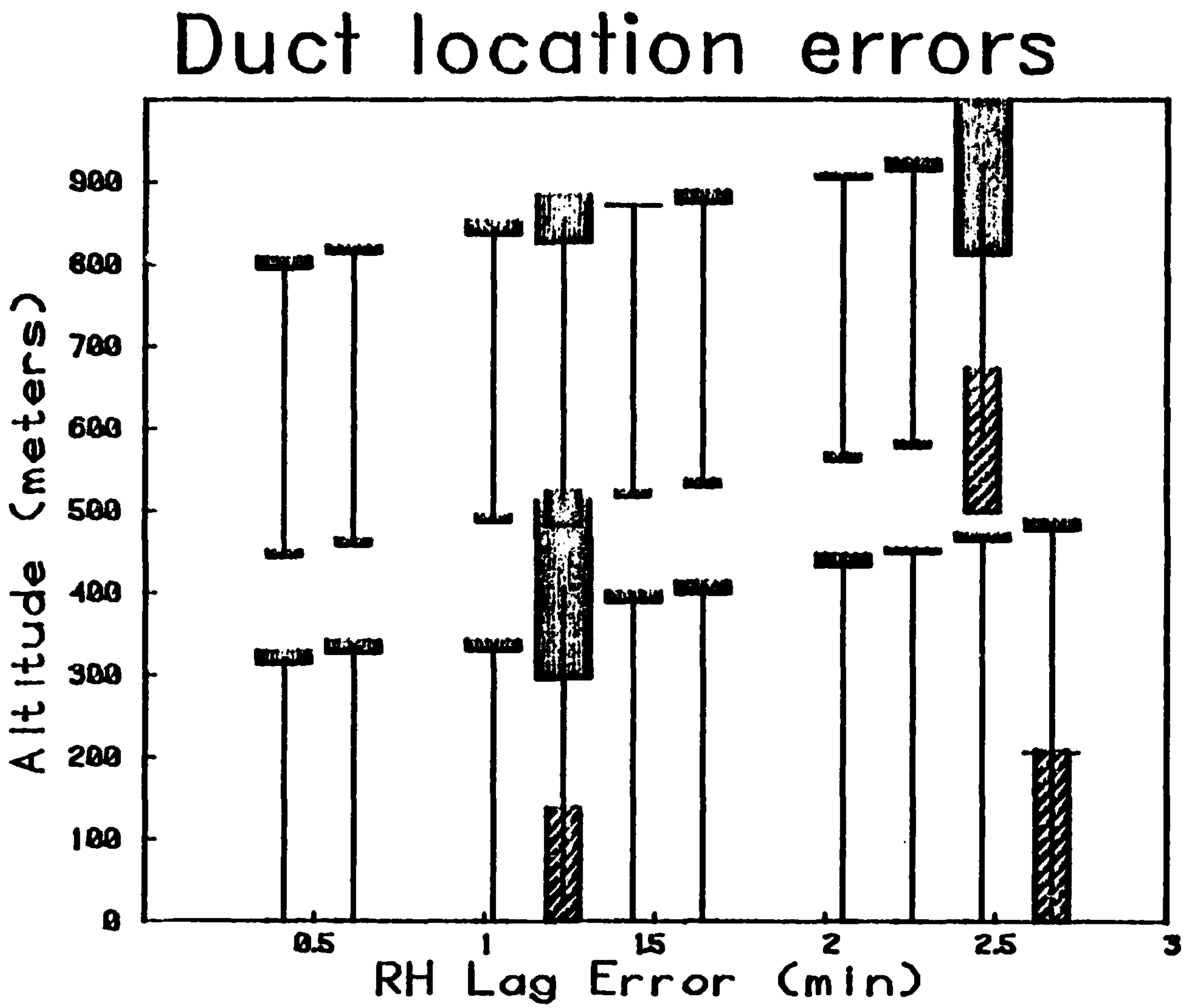


Fig 7 A plot of the duct location errors produced by lag errors in the responce of the relative humidity device.

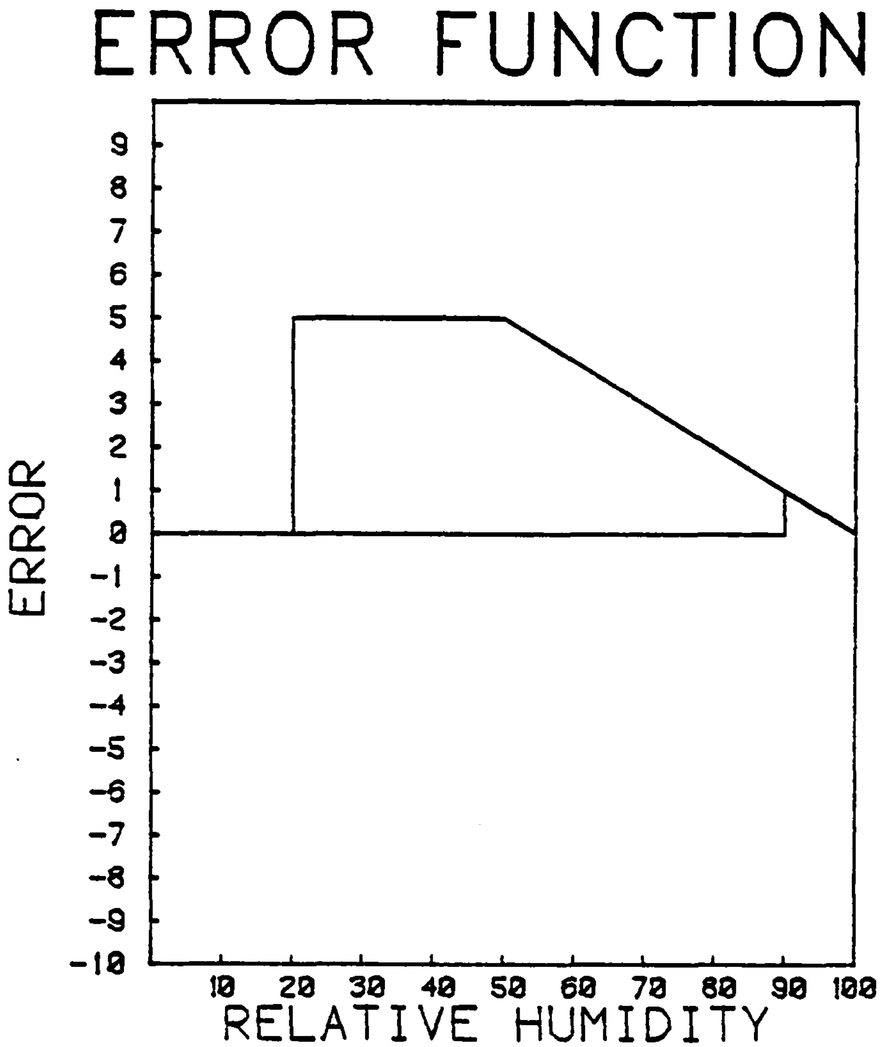


Fig 8 A plot of a hypothetical hysteresis error function used in the analysis to obtain figure 9.

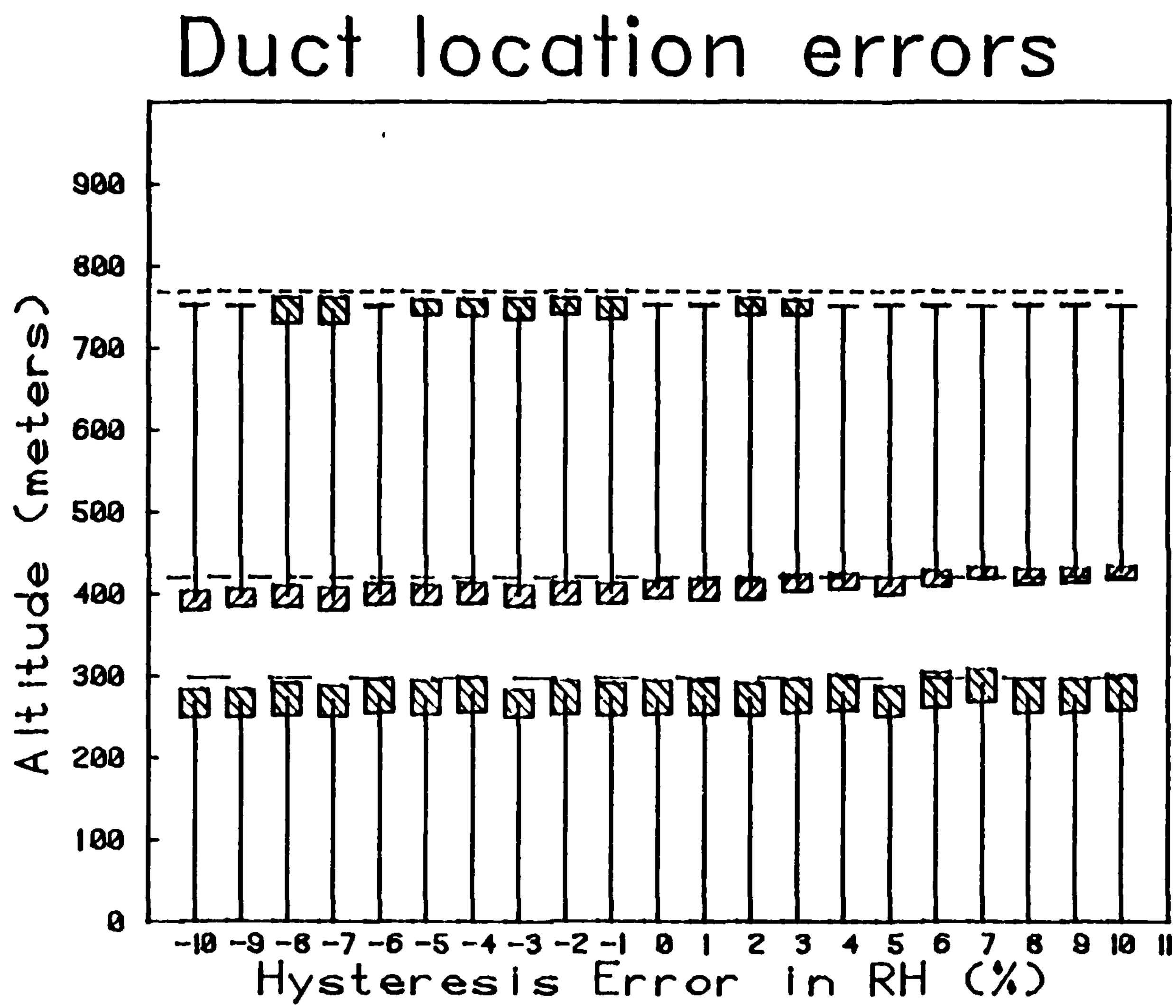


Fig 9 A plot of the duct location errors produced by hysteresis errors in the measurement of relative humidity.

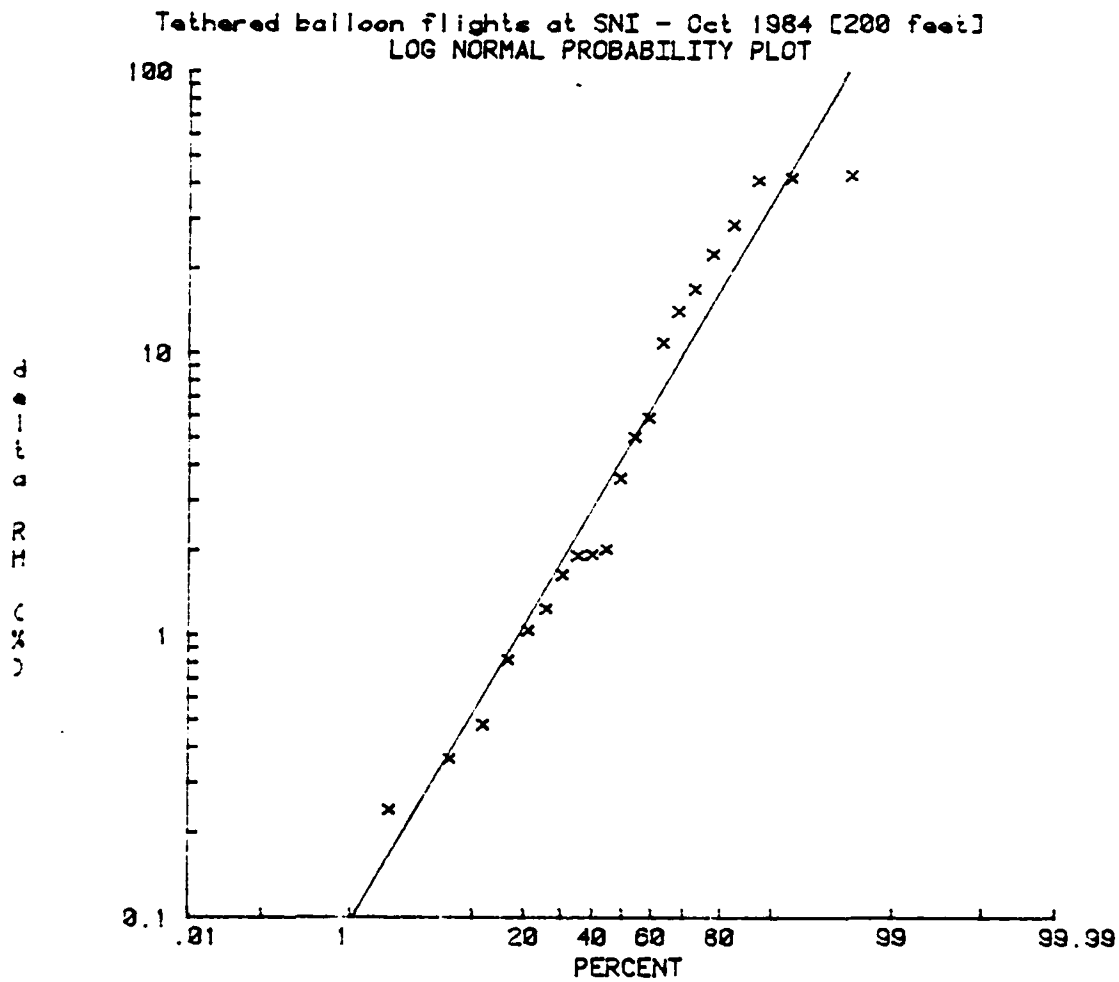


Fig 10 A log normal probability plot from the tethered balloon flights at 200 feet showing the differences between up and down measurements of relative humidity.

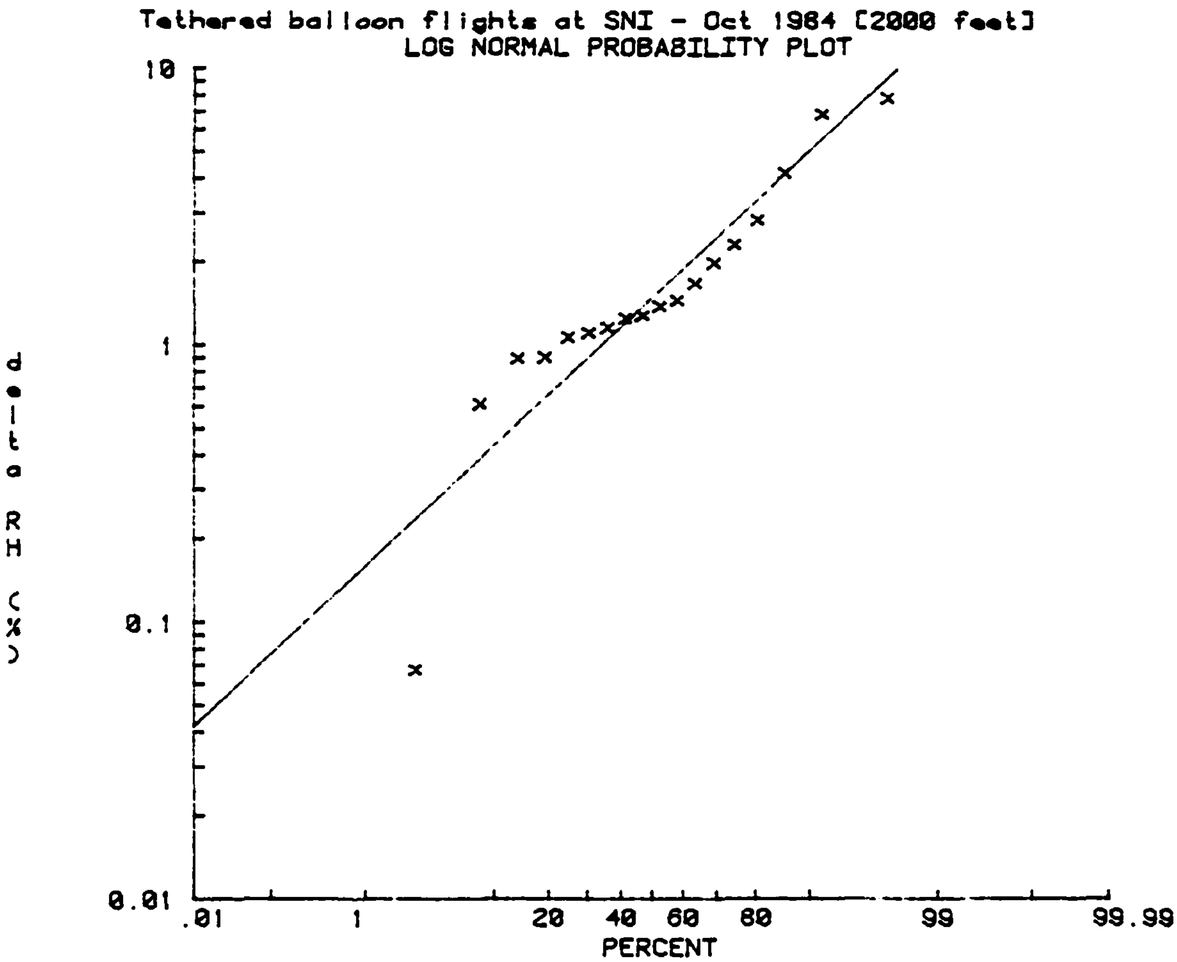


Fig 11 A log normal probability plot from the SNI tethered balloon flights at 2000 feet showing the differences between up and down measurements of relative humidity.

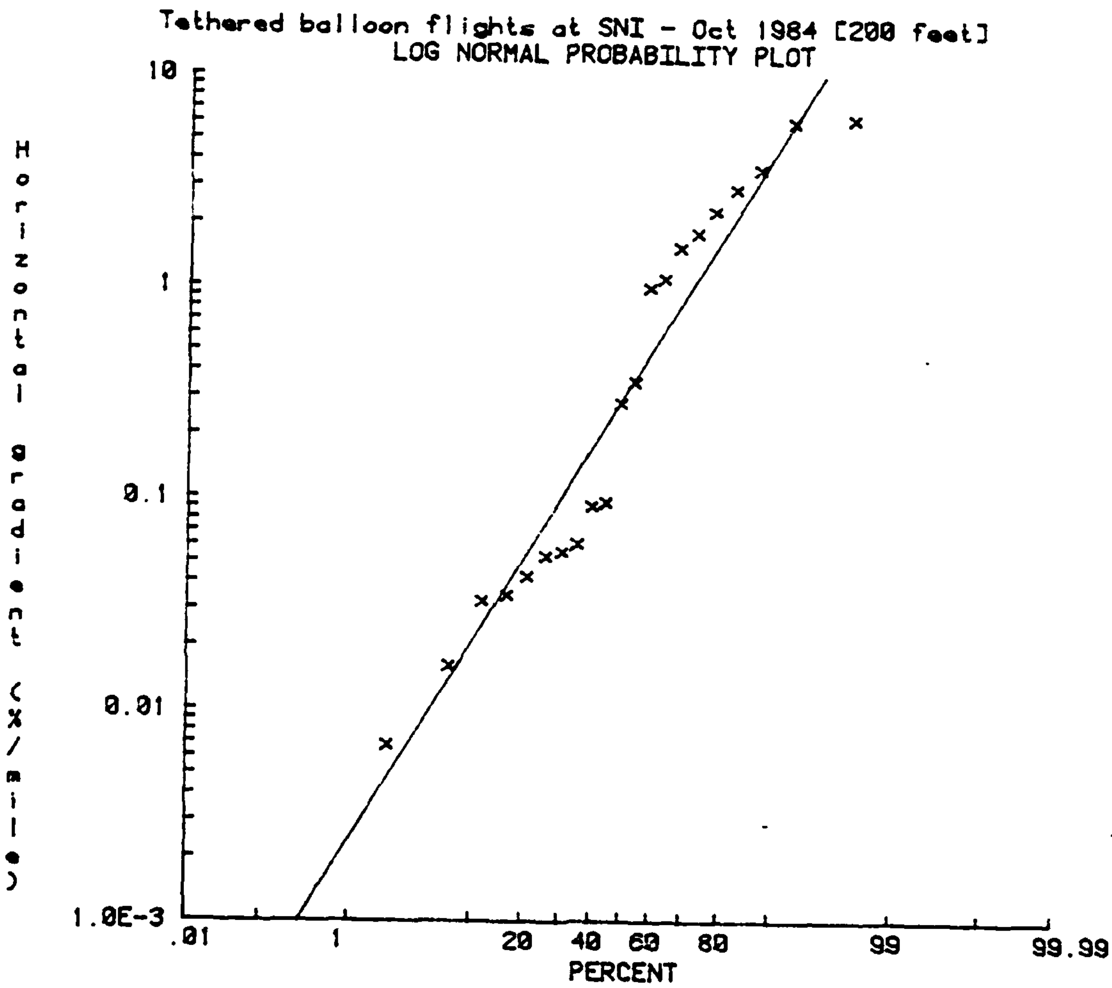


Fig 12 A log normal probability plot from the SNI tethered balloon flights at 200 feet showing the estimated horizontal gradients in relative humidity.

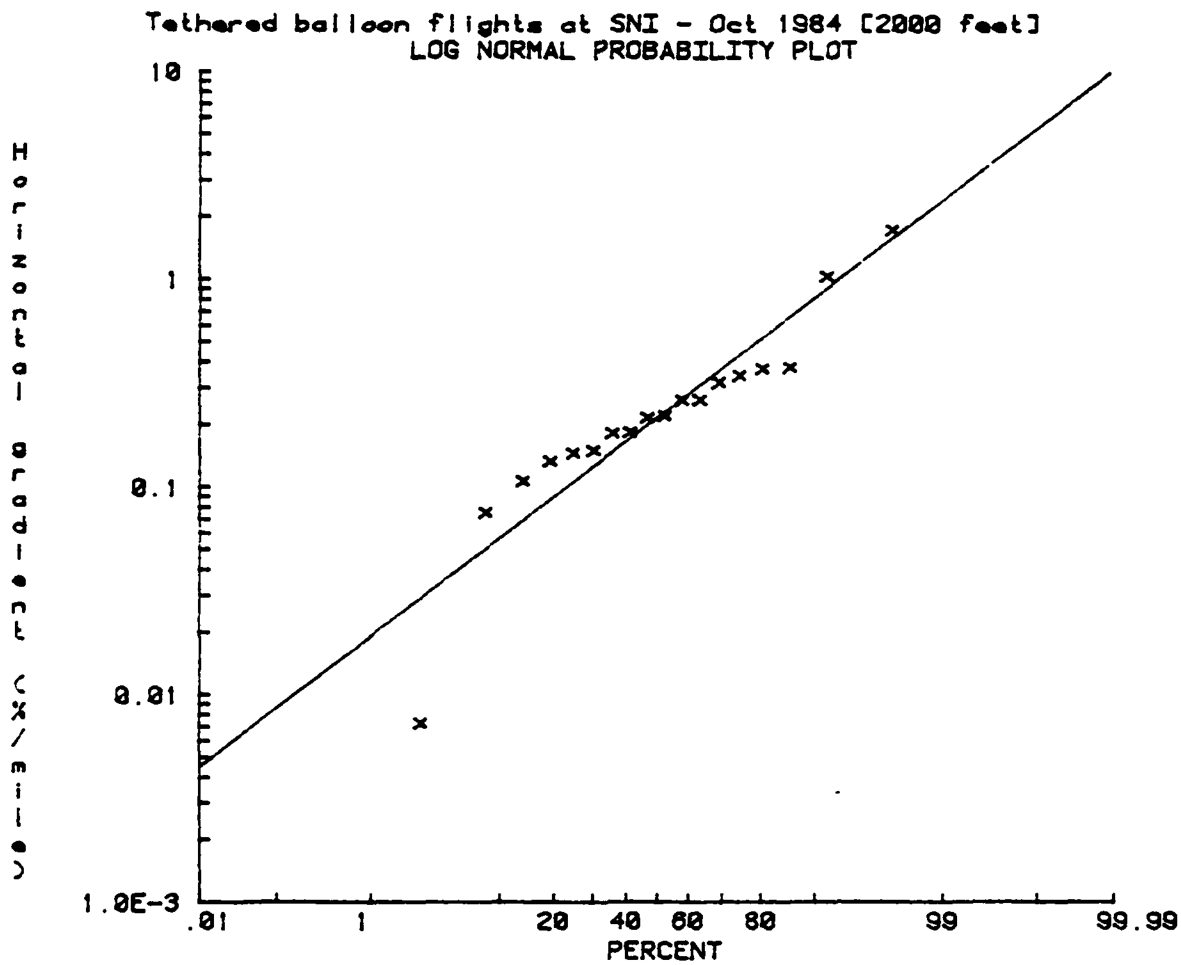


Fig 13 A log normal probability plot from the SNI tethered balloon flights at 2000 feet showing the estimated horizontal gradients in relative humidity.

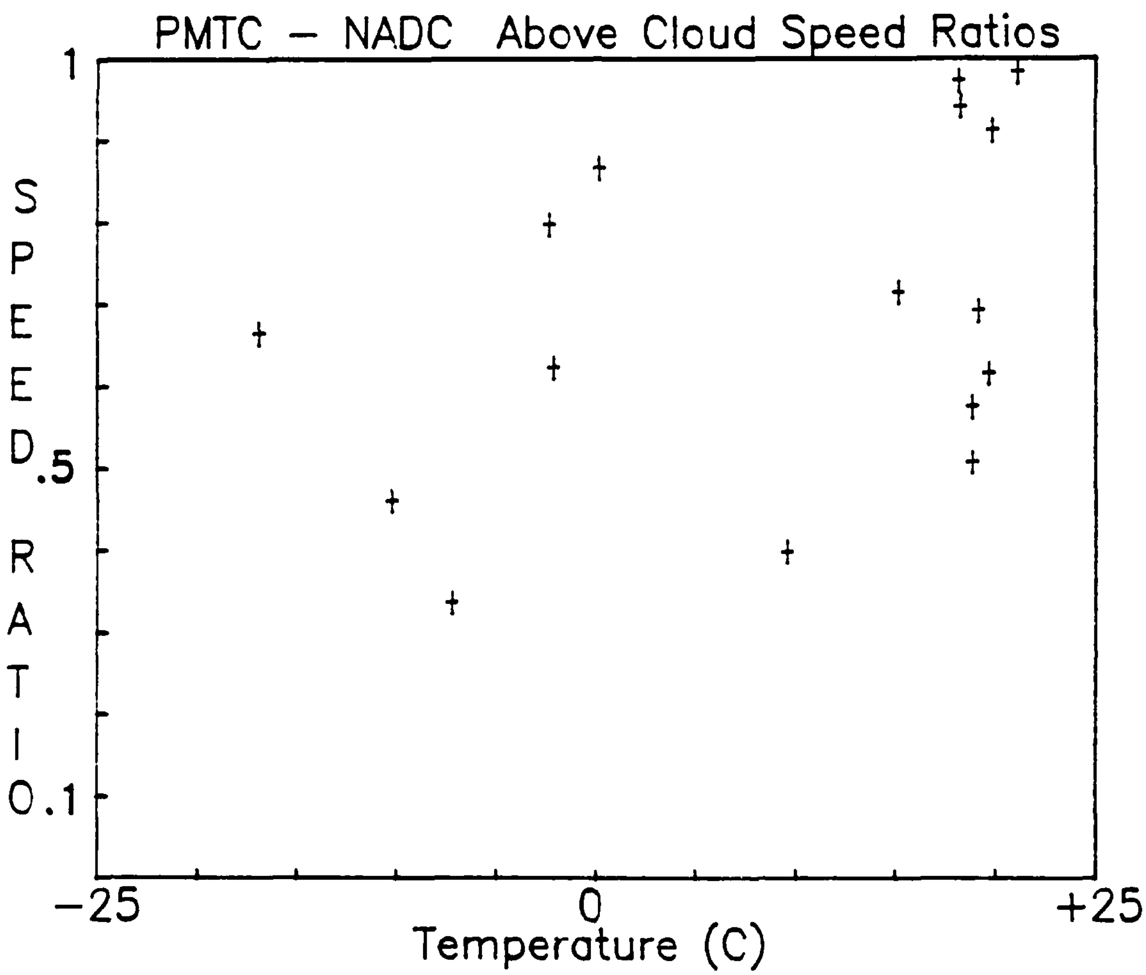


Fig 14 A plot of the speed ratio of Vaisala versus Viz relative humidity responses from the PMTC - NADC tests.

9. REFERENCES

Annema, K.H., Monna, W.A.A., and Muller, S.H., (1984); "A Comparative Investigation of Three Commercial Radiosonde Systems", W.M.O.: Instruments and Observing Methods, Report No. 15, papers presented at the W.M.O. Technical Conference on Instruments and Cost-Effective Meteorological Observations (TECEMO), Noordwijkerhout, Netherlands, 24-28 Sept 1984.

Antikainen, V and V. Hyvonen, (1983); "The Accuracy of Vaisala RS80 Radiosonde", Paper 8.1 in preprint vol. of Fifth Symposium on Meteorological Observations and Instrumentation, April 11-15, 1983 Toronto, Canada, (A.M.S publishing).

Gerber, H.E., (1985);Tethered Balloon Measurements at San Nicolas Island (Oct.,1984): Instrumentation, Data Summary, Preliminary Data Interpretation, NRL Memorandum Report #### (in press).

Hattan, C.P., Patterson, W.L., Hitney, H.V., Paulus, R.A., Anderson, K.D., and Lindem, G.E., (1983); IREPS revision 2.2 User's Manual, NOSC Tech. Doc. #659. ADB081074

Helvey, R.A., (1979); "Preliminary Assessment of Temperature Induced Radiosonde Humidity Errors and Effects of Apparent Low Level Refractive Structures", PMTC Technical paper #TP-79-09. ADA068670

Helvey, R.A., (1982); "Guidelines for Correction of Radiosonde Derived Refractive Profiles and Climatologies", PMTC Tech. Pub. #TP000002. ADA124351

Helvey, R.A., (1983); "Radiosonde errors and spurious surfacebased ducts", Institution of Electrical Engineers Proceedings, Vol 130, Pt F, #7, p.643.

Helvey, R.A., (1985); personal communication.

List, R.J.,(1968); Smithsonian Meteorological Tables, sixth revised edition , p350, Smithsonian Institution press, Washington, D.C.

Marchgraber, R.M. and Grote, H.H., (1965); "The Dynamic Behavior of Carbon Humidity Element ML-476", Ch 34 in: Humidity & Moisture - Measurement and Control in Science and Industry , Vol 1, A. Wexler, editor-in-chief, R. E. Ruskin, Editor, Reinhold, NY.

Mathews, D. A., (1965); "Review of the Lithium Chloride Radiosonde Hygrometer", Ch 23 in: Humidity & Moisture - Measurement and Control in Science and Industry , Vol 1, A. Wexler, editor-in-chief, R. E. Ruskin, Editor, Reinhold, NY.

Nash J., (1984); "Multiple-Flight Radiosonde Intercomparison", W.M.O.: Instruments and Observing Methods Report No. 15, papers presented at the W.M.O. Technical Conference on Instruments and Cost-Effective Meteorological Observations (TECEMO), Noordwijkerhout, Netherlands, 24-28 Sept 1984.

Phillips, P.D., Richner, H., Joss, J., and Ohmura, A., (1980/81); "ASOND-78: An Intercomparison of Vaisala, Viz, and Swiss Radiosondes", Pure and Applied Geophysics, Vol 119, pp 259-277.

Phillips, P.D. and H. Richner, (1983); "SONDEX - The Alpex Radiosonde Intercomparison", paper 8.1 in: preprint vol. of Fifth Symposium on Meteorological Observations and Instrumentation, April 11-15, 1983 Toronto, Canada, (A.M.S publishing).

Pratt, R.W., (1985); "Review of Radiosonde Humidity and Temperature Errors", Journal of Atmospheric and Oceanic Technology, Vol 2, p 404.

Richner, H. and Phillips, P.D., (1981); "Reproducibility of VIZ Radiosonde Data and Some Sources of Error", JAM, Vol 20, pp 954- 962.

Showalter, A.K., (1965); "State of the Art Survey on the Application of Hygrometry to Meteorology", Ch 54 in: Humidity & Moisture - Measurement and Control in Science and Industry . Vol 2, A. Wexler, editor-in-Chief, E. J. Amdur, Editor, Reinhold. NY.

Sniscak, J., (1985a); unpublished work

Sniscak, J., (1985b); "Test and Evaluation Report of Mini-Refraction sonde system (MRS)", NADC report

Stine, S.L., (1965); "Carbon Humidity Elements - Manufacture, Performance, and Theory", Ch 33 in: Humidity & Moisture - Measurement and Control in Science and Industry , Vol 1, A. Wexler, editor-in-Chief, R. E. Ruskin, Editor, Reinhold, NY.

Werst, M.C., (1980); "Anomalous RF Propagation Effects in an Ocean Environment", NADC Report #:NADC-79087-30, Contract #:N62269-79-C-0357 Inter-Discipline Engineering Associates.

END
FILMED

5-86

DTIC